

SATELLITE PICTURES AND METEOROLOGICAL ANALYSES OF A DEVELOPING LOW IN THE CENTRAL UNITED STATES¹

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ABSTRACT

TIROS I satellite pictures for a 3-day period about a developing "Low system" over the central United States are shown. Cloud distribution about surface fronts and upper-air troughs was examined and compared to the "ideal" (classical) distribution. The pictures and analyses reveal that cloud patterns were significantly changed by strong subsidence and advection of dry air along a low-level wind maximum. The cloud patterns when compared to the 600-mb. vertical motions computed routinely by the Joint Numerical Weather Prediction Unit showed only partial agreement.

A strong relationship between low cloud cover and surface relative humidity was found; this relationship may be useful under certain conditions in determining the stability of the air over areas where upper-air data are sparse.

1. INTRODUCTION

This study was undertaken to investigate the cloud distribution, as indicated by satellite pictures in addition to the usual synoptic methods, for several stages in a developing low pressure system in the central United States. Analyses of the pictures and meteorological data were made in the following manner:

1. Latitude-longitude grids were drawn and superimposed on selected satellite pictures taken over the low pressure system on May 19 through May 21, 1960.

2. To the pictures were added surface analyses and selected data. For example see figure 1.

3. Surface analyses and upper-air analyses were made. (Only the surface maps are shown with the 500-mb. trough positions superimposed.) For example see figure 3b.

4. Simplified schematic diagrams made from cloud pictures were transferred to polar stereographic maps of cloud data and frontal positions. Over the United States cloud types were taken from the nearest 3-hourly observation time (i.e., 1800 or 2100 GMT). For example see figure 3a.

5. The relationships between cloud distribution and (a) synoptic situation, (b) low-level wind maximum, (c) vertical motions, (d) surface relative humidity, were examined for each of the three days.

2. CLOUD DISTRIBUTIONS AND ANALYSES, MAY 19, 1960

Figures 1 and 2 picture the cloud fields which are schematically represented on figure 3a. Figure 3b is the corresponding surface analysis with the 500-mb. trough position superimposed.

SYNOPTIC SITUATION

Figure 3a shows that the bulk of the cloudiness associated with the surface cold front lay well to the rear of the front and to the northwest of the wave centered in southern Kansas. Further, the region immediately about and ahead of the cold front was clear, with the exception of the small zones of scattered to broken cumulus clouds. This type of distribution differs completely from the "ideal" distribution model [1] in which the bulk of the cloudiness lies ahead of the cold front with rapid clearing to the rear.

The bulk of the cloudiness to the rear of the cold front was located in and ahead of the 500-mb. trough and agreed with the findings of Oliver and Oliver [2] that clouds are located at and ahead of their respective upper-air troughs. There were small zones of cloudiness behind the 500-mb. trough; these however, were probably the result of orography since they lay over the highest peaks of the Rockies.

The brightness and high reflectivity of the homogeneous-appearing clouds immediately ahead of the warm front (fig. 2) can probably be attributed to the high water content of the clouds since continuous precipitation was reported in this area. This low cloud mass, whose trailing edge coincided closely with the surface warm front, extended about 300 miles ahead of the front where the cloud deck abruptly rose to 10,000 ft. or higher and extended about 600 mi. ahead of the front. This cloud distribution conformed nicely with the "ideal" warm frontal model [1].

LOW-LEVEL WIND MAXIMUM

At 1800 GMT, May 19, a low-level wind maximum at 5,000 ft. was located near Louisville, Ky. and extended into upper Michigan. A weaker wind maximum (about 30-40 kt.) also at 5,000 ft. extended through central

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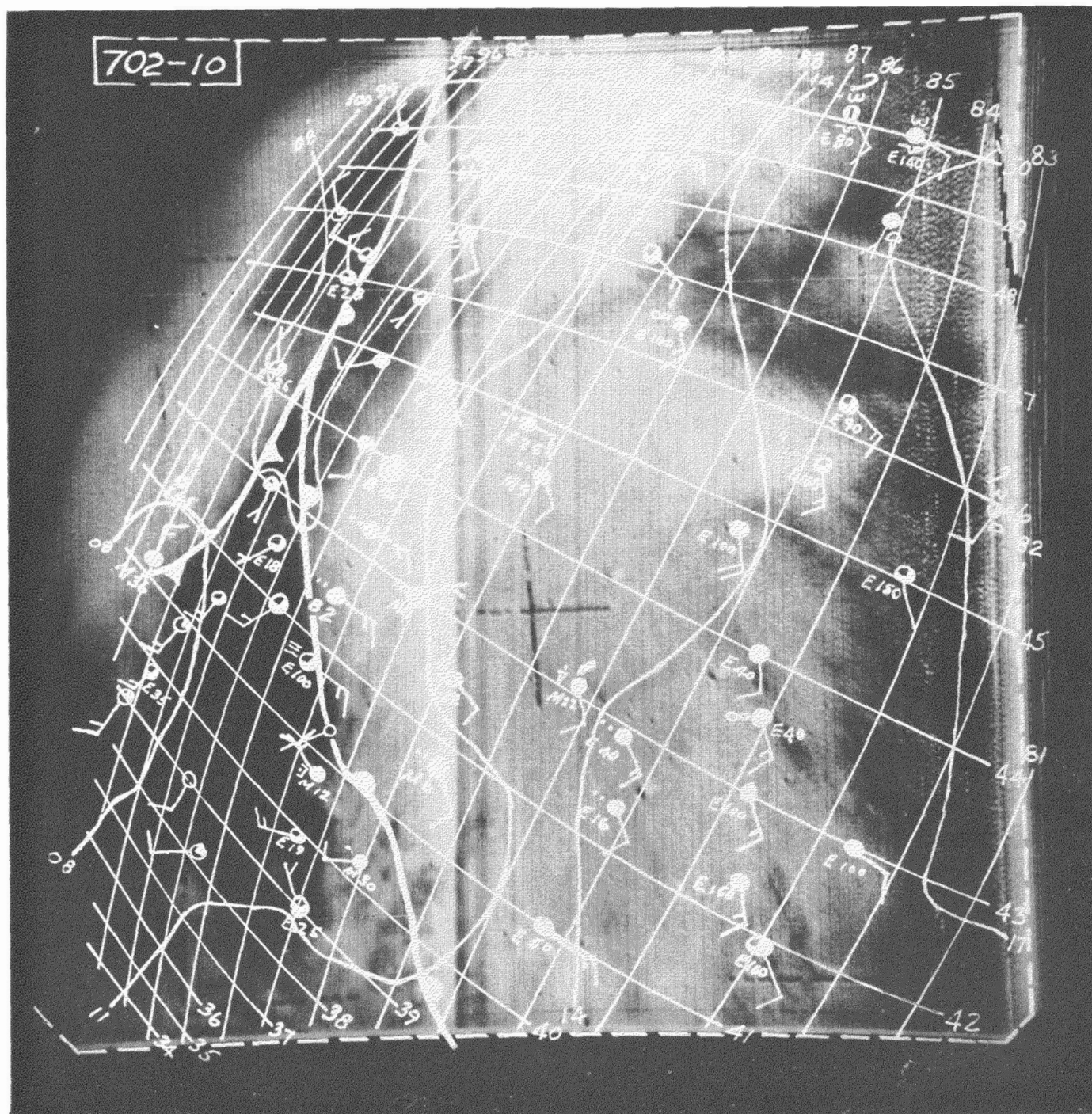


FIGURE 2.—TIROS picture for 2003 GMT, May 19, 1960 with data and latitude-longitude grids superimposed.

case may not be valid due to the fact that vertical motions computed with the present JNWP model reflect only large-scale motion, while cloud fields are frequently produced by mesoscale systems and convective overturning.

SURFACE RELATIVE HUMIDITY

During the course of this study, it was noticed that the surface relative humidity patterns were well correlated with cloud cover below 5,000 ft. Although the low clouds on all three days largely reflected the influence of after-

noon convection, some low ceilings occurred with fronts where the same humidity relationship was evident, though less marked.

A reasonable explanation may be that in areas where surface heating produces convection, a mixed subcloud layer should display the same humidity pattern at the surface and at cloud level. Even under frontal clouds, mixing may occur in the subcloud layer, but it is likely that higher humidities might be produced by the cloud



FIGURE 3.—(a) Schematic nephanalysis 2001-2003 GMT, May 19, 1960. Opaque-appearing broken and overcast regions are represented by hatching and stippling, respectively. Clear, scattered, and hazy-appearing areas are left unshaded. (b) Surface data and analysis 2000 GMT, May 19. (c) Broken (hatched) and overcast (stippled) cloud ceilings below 5,000 ft. with surface relative humidity isopleths (percent), 2000 GMT, May 19, 1960.

cover itself by holding down temperatures during the afternoon, thus preventing the afternoon decrease of relative humidity that accompanies heating with a constant specific humidity. In addition, of course, clouds associated with a front may precipitate, in which case there should be a very good correlation between cloud and humidity.

Some practical use might be made of this relationship, at least over convective areas, because it appears that the agreement or disagreement of surface humidity with low cloud ceilings depends largely on vertical mixing. This

mixing, in turn, is a function of the stability; i.e., where stability is strong surface heating can produce only few clouds, and where the stability is weak the heating quickly produces a cloud ceiling. Therefore, where high surface humidities can be inferred independently, lack of a cloud ceiling implies great stability, and a low cloud ceiling indicates instability. Even qualitative information of this type over data-free regions would be valuable.

Figure 3c shows the surface humidity patterns superimposed on the low cloud nephanalysis for 2000 GMT, May 19. On this and subsequent figures, isopleths of

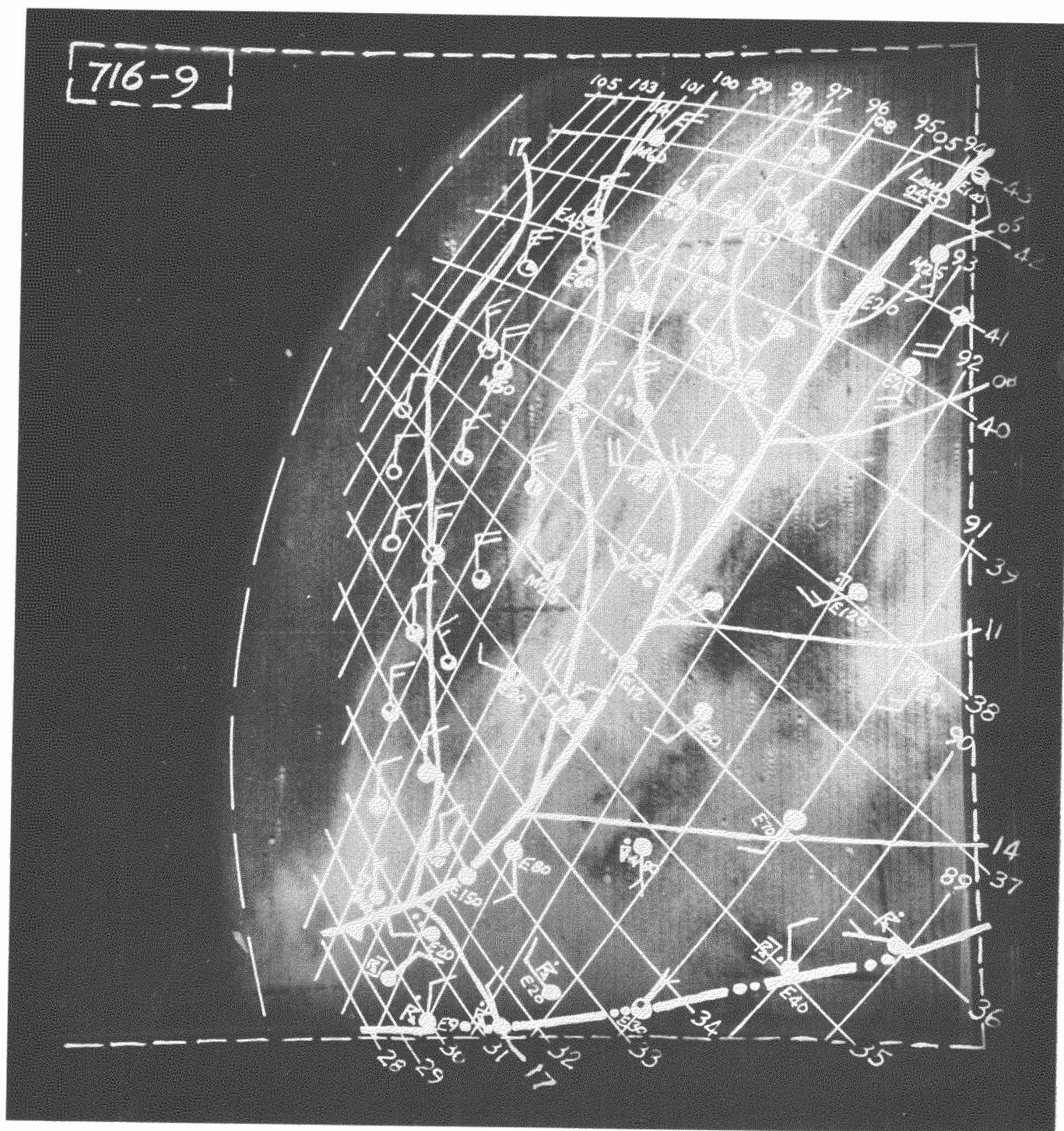


FIGURE 4.—TIROS picture for 1908 GMT, May 20, 1960 with data and latitude-longitude grids superimposed.

relative humidity were drawn to station data and therefore do not display the detail of the low cloud nephalanalyses which were made from station reports and cloud pictures.

Allowing for these differences, it is seen that in almost all of the areas where low cloud ceilings existed, the surface humidity was greater than 70 percent. Only Belleville, Ill., Dayton, Ohio, McAlester, Okla., and St. Louis, Mo. failed to report low cloud ceilings. Where the humidity was below 50 percent, almost no low ceilings were reported.

Only Waco, Tex., Cheyenne, Sheridan, and Yellowstone Park, Wyo. reported low ceilings in this case.

Examination of the vertical temperature distribution between 1 and 2 km. at 0000 GMT, May 20, for the exceptions showed that the lapse rates were quite small (stable conditions) over the four stations where the humidity was greater than 70 percent and no low cloud ceilings existed. Conversely, the lapse rates over the four stations where low ceilings existed over low surface humidity

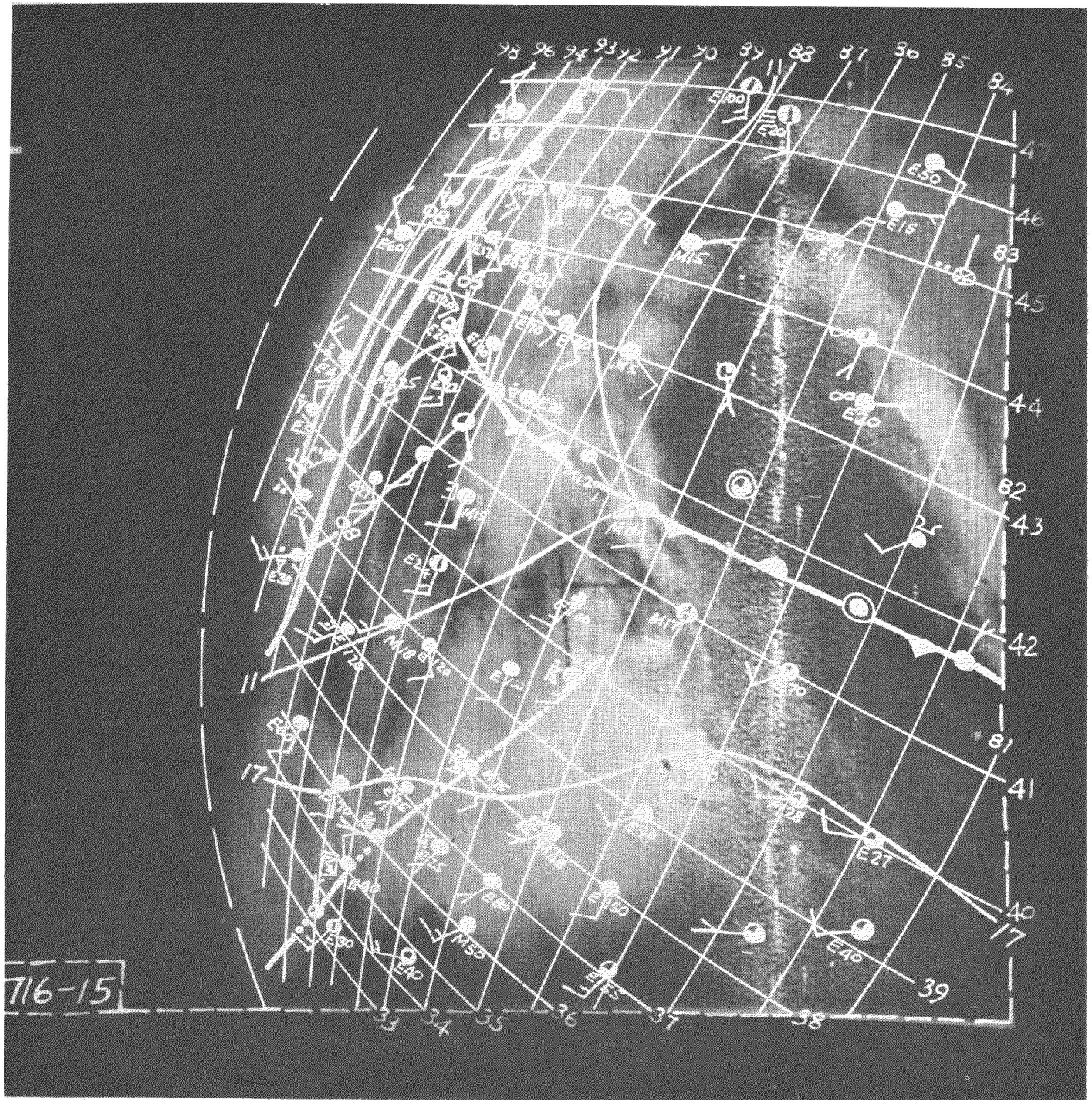


FIGURE 5.—TIROS picture for 1910 GMT, May 20, 1960 with data and latitude-longitude grids superimposed.

were quite large (unstable conditions)—a curious relationship noted on the other days as well, but a relationship that is not of direct utility in the context just mentioned.

3. CLOUD DISTRIBUTIONS AND ANALYSES, MAY 20, 1960

Figures 4 and 5 show the cloud patterns about the Low and frontal systems at 1908 and 1910 GMT, while figures 6 and 7 show the area to the north at 2053 and 2054 GMT.

The cloud schematic diagrams of these pictures were combined and are shown in figure 8a. Figure 8b gives the corresponding surface analyses with the 500-mb. trough superimposed.

SYNOPTIC SITUATION

By 1900 GMT, May 20, the surface Low in Manitoba, Canada had filled and a new low center had developed in Iowa along the cold frontal trough. This development marked the first strong cyclonic circulation of the low

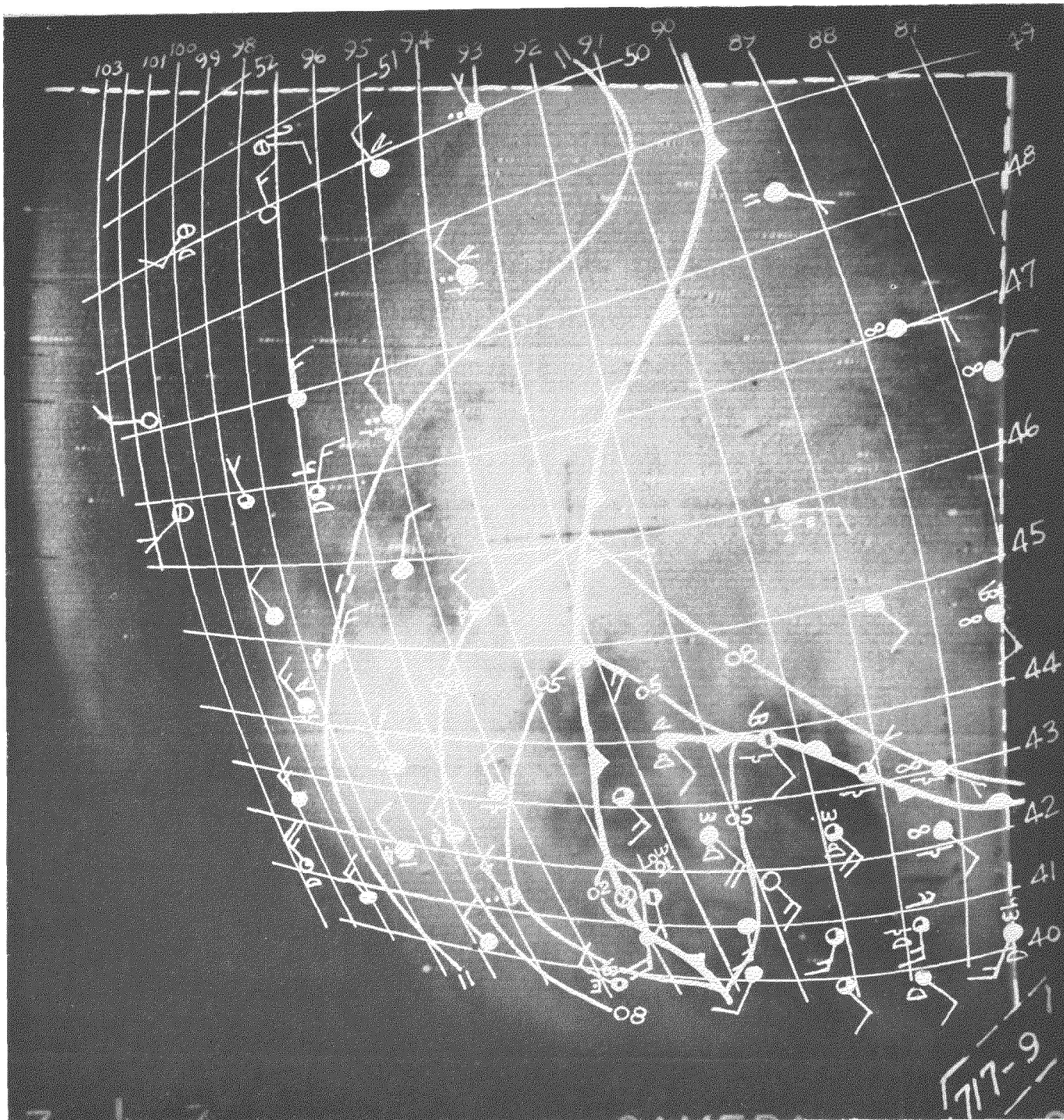


FIGURE 6.—TIROS picture for 2053 GMT, May 20, 1960 with data and latitude-longitude grids superimposed.

system. Both the warm and cold frontal systems in Iowa remained stationary, while the southern portion of the cold front and the eastern portion of the warm front moved slowly eastward and northeastward, respectively.

A very active squall line had developed and extended all the way from Indianapolis, Ind. to Galveston, Tex. The low-level southwesterly winds which extended northward through central Texas during the development of the squall line on the night of May 19 (between 0000 and

0300 GMT, May 20) and the presence of a zone of low-level stability (small lapse rates) offer strong support to the theories of Rossby [4] and Cahn [5] and the work of Tepper [6] in which he speculates that "The development of eastward propagating pressure-jump lines (associated with squall lines) was due to the addition of momentum to the low level southerly flow by a marked increase in the southerly component of winds during the night."

The cloud field had become organized into a broad

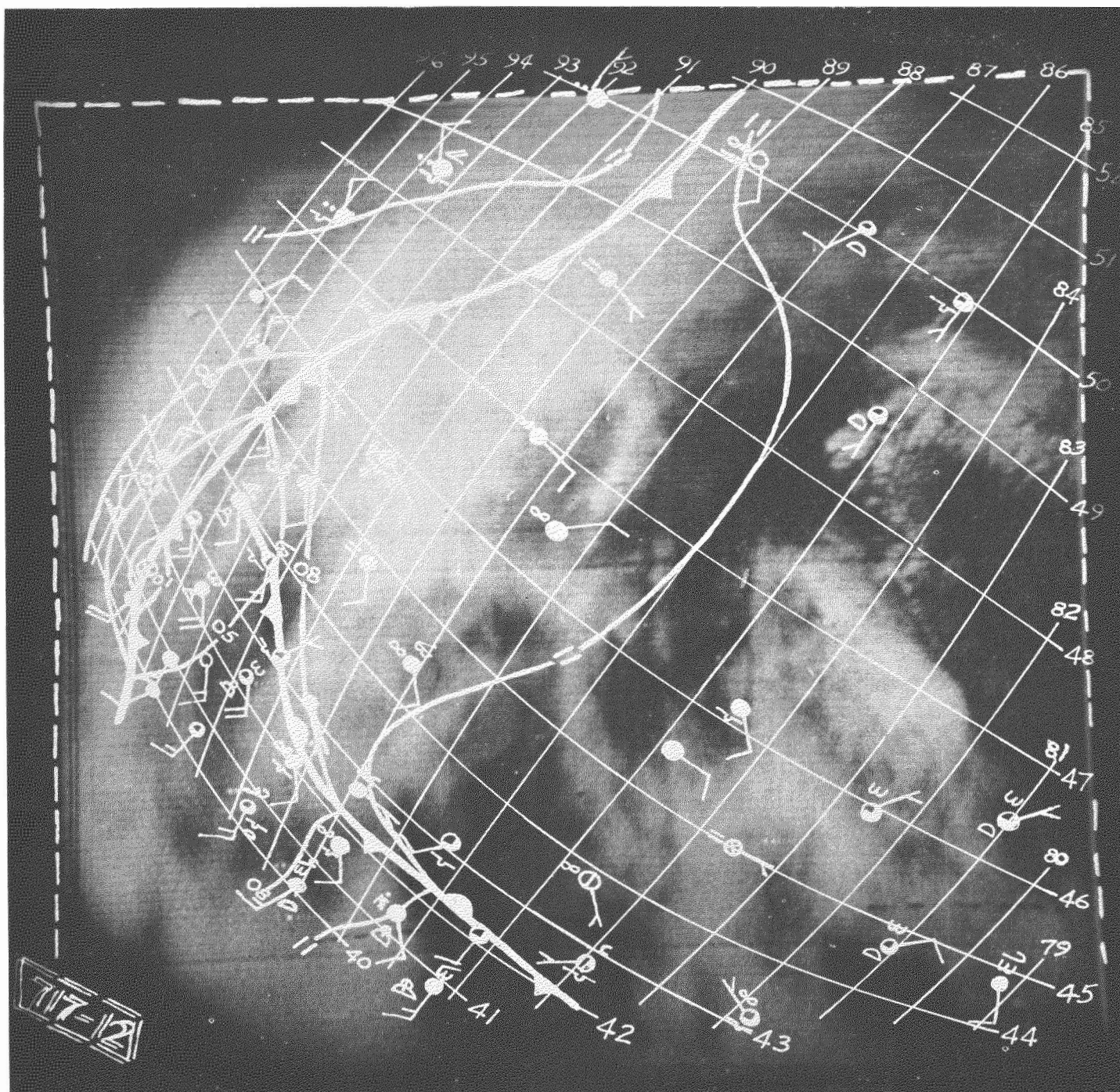


FIGURE 7.—TIROS picture for 2054 GMT, May 20, 1960 with data and latitude-longitude grids superimposed.

north-south band (fig. 8a). The cloud distribution which lay well behind the surface cold front on the previous day had now assumed a position over the front and the squall line in a pattern following the "ideal" cold frontal model. Middle and high clouds still remained at and ahead of the 500-mb. trough; but by the steepening of the surface to 500-mb. trough slope from 1/180 to 1/50, middle and higher clouds were brought over the low cloud deck thus forming the broad north-south band with rapid clearing to the rear.

The breaks in the overcast band (fig. 8a) indicate the separation between that portion of the cloud band associated with the cold front and that associated with the squall line. These small clearing areas between 92° and 93° W. and the weakening of the cloud band at about 35° N. are best viewed on figure 4. It was in this region, at this time, that the clear tongue photographed on the next day (May 21) was beginning to form.

On figures 5 and 7 note that the cloud field ahead of the warm front (now stationary) had become less extensive,

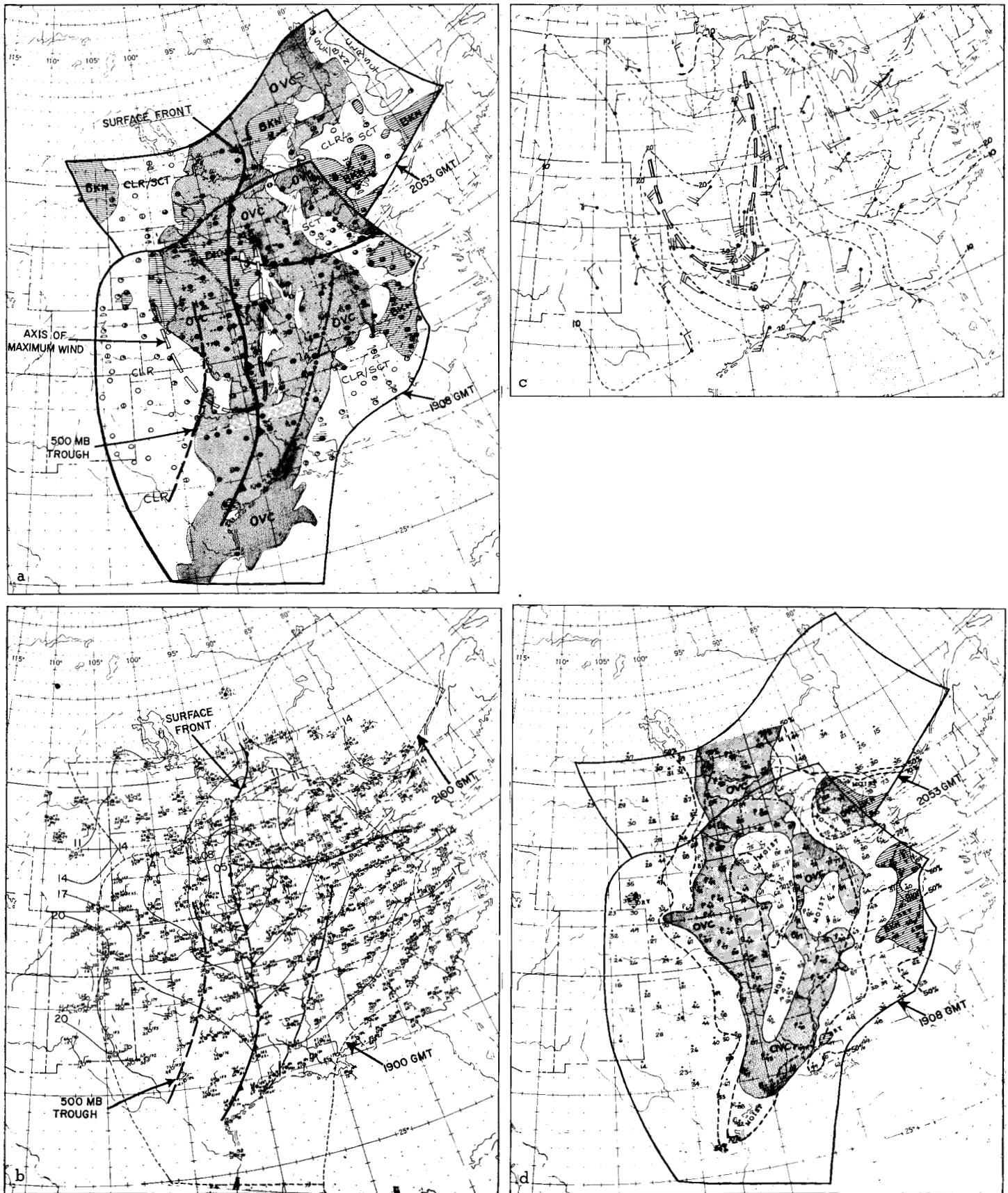


FIGURE 8.—(a) Schematic nephanalysis 1908–1910 and 2053–2054 GMT, May 20, 1960. Broken line shows axis of maximum wind at 5,000 ft. (from map c). (b) Surface data and analyses 1900 and 2100 GMT, May 20, 1960. (c) Wind data, axis of maximum wind, and isobars (kt.) at 5,000 ft., 1800 GMT, May 20, 1960. (d) Broken and overcast cloud ceilings below 5,000 ft. with surface relative humidity isopleths (percent) 1900 and 2100 GMT, May 20, 1960.

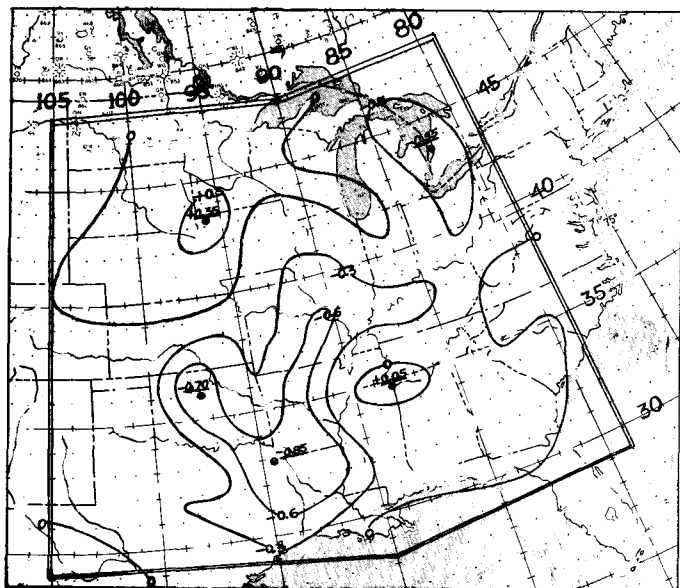


FIGURE 9.—850-mb. horizontal moisture advection ($\text{gm. kg.}^{-1} \text{hr.}^{-1}$), 0000 GMT, May 21, 1960.

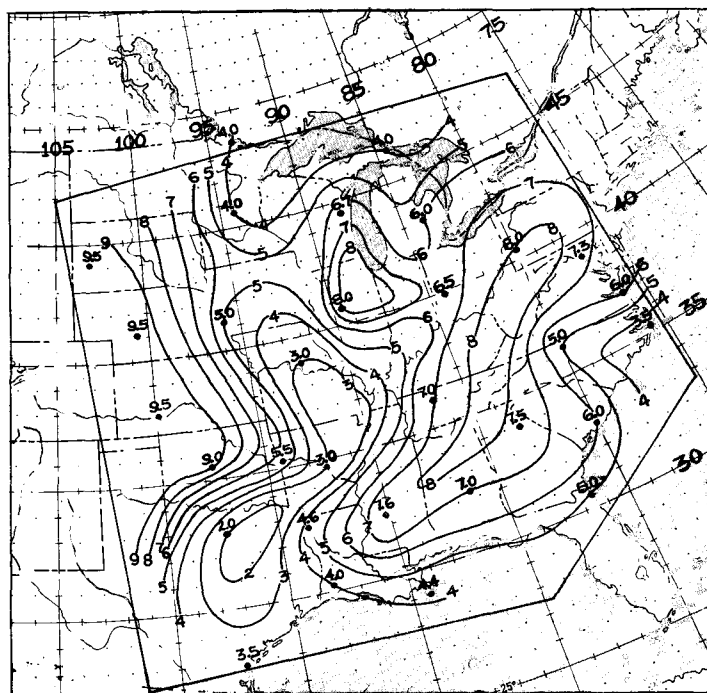


FIGURE 10.—Lapse rates between 1 and 2 km. ($^{\circ}\text{C. km.}^{-1}$), 0000 GMT, May 21, 1960.

less dense, and somewhat disorganized from that seen on the previous day. The zone of scattered clouds extending across and ahead of the front in the vicinity of 85° W. is believed to have been caused by horizontal advection of dry air and is discussed below.

LOW-LEVEL WIND MAXIMUM

Figure 8c shows the wind analysis at 1800 GMT, May 20, 1960 for the 5,000-ft. level; the axis is also shown on figure 8a. The clearing in the region of the maximum wind

and its long narrow shape suggest it may have been produced by the advection of dry air in the low-level jet.

To examine this possibility, the horizontal advection of moisture was computed for 0000 GMT, May 21, and is shown in figure 9. This computation revealed that the strongest advection was taking place south of the wind maximum. The advection of dry air across the stationary front near 85° W. was primarily the result of a large moisture gradient while the advection to the south of the jet maximum was caused by a large moisture gradient as well as high wind speeds. Because these large moisture gradients existed within the same air mass, it appears that vertical motions were creating extensive pockets of dry air, a matter that is investigated next.

VERTICAL MOTIONS

The 600-mb. JNWP vertical motions, interpolated for picture time, showed upward motions between 0 and 1 cm. sec.^{-1} over the eastern half of the United States with a very small zone of upward motion greater than 1 cm. sec.^{-1} centered near Jackson, Miss. The zero isopleth closely delineated the trailing edge of the broad north-south cloud band to the rear of the cold front. The clearing associated with the low-level wind maximum, the zone of scattered clouds across the stationary front in the vicinity of 85° W., and the region of clear to scattered clouds ahead of the squall line (see fig. 8a) were all located in the region of computed large-scale upward motion.

SURFACE RELATIVE HUMIDITY

Figure 8d shows the 1900 and 2100 GMT surface humidity patterns superimposed on the corresponding low cloud nephanalysis for May 20, 1960. The 70 percent humidity isopleth again showed a tendency to outline the regions of low cloud ceilings while there was generally an absence of low cloud cover where the humidity was below 50 percent.

Of the 215 stations shown, 41 stations violated the stipulated 50 percent and 70 percent limitations: 8 stations, located in areas labeled "DRY" showed broken low cloud ceilings with surface humidities less than 50 percent; 33 stations, located in areas labeled "MOIST", had humidities greater than 70 percent but no low cloud ceilings.

Examination of the lapse rates about the 850-mb. level approximately 5 hours after picture time indicated that the violations were again related to the low-level stability. In figure 10, which shows the lapse rates between 1 and 2 km. for 0000 GMT, May 21, it is seen that the lapse rates over the areas corresponding to the regions labeled "MOIST" were quite stable; while over the regions labeled "DRY" the lapse rates were quite unstable.

4. CLOUD DISTRIBUTIONS AND ANALYSES, MAY 21, 1960

Figures 11 and 12 show the spiral cloud band about the cold front and the clear tongue to the rear at 1816 and 1817 GMT. Figures 13 and 14 show the northern por-

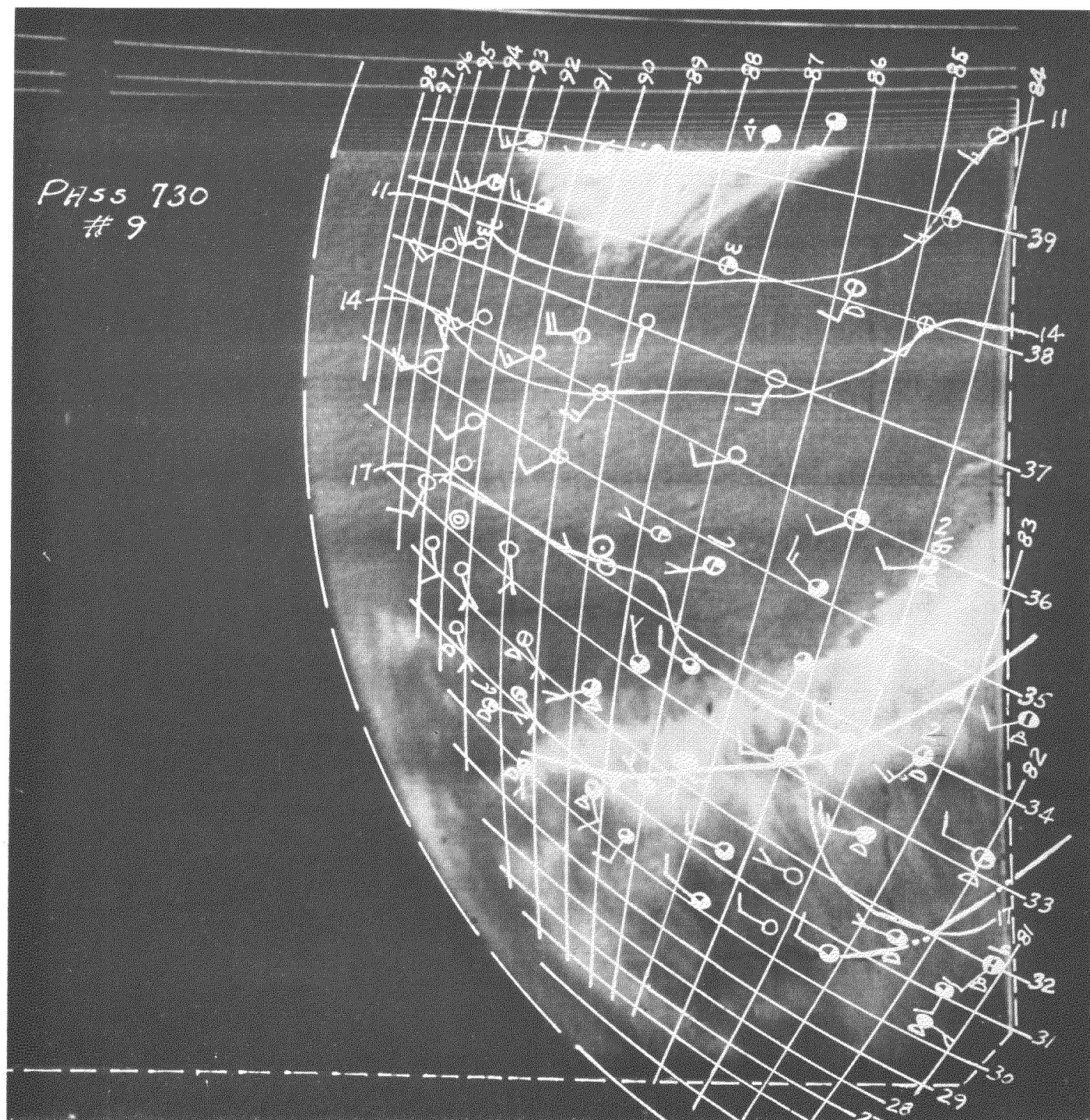


FIGURE 11.—TIROS picture for 1816 GMT, May 21, 1960 with data and latitude-longitude grids superimposed.

tion of the clear tongue and the spiral band associated with the vortex at 2000 and 2001 GMT. The combined schematic nephanalysis for these photos is shown in figure 15a. Figure 15b gives the corresponding surface analyses. The 500-mb. trough is not shown because there was uniform curvature about the closed system with no pronounced trough.

SYNOPTIC SITUATION

By 1800 GMT, May 21, the surface low center had moved 180 mi. northeastward while the upper-air Low had deepened, become closed, and moved approximately 300 mi. to the northeast; this movement made the axis of the low system very nearly vertical. During the previous 23 hours, the winds in the low levels had under-

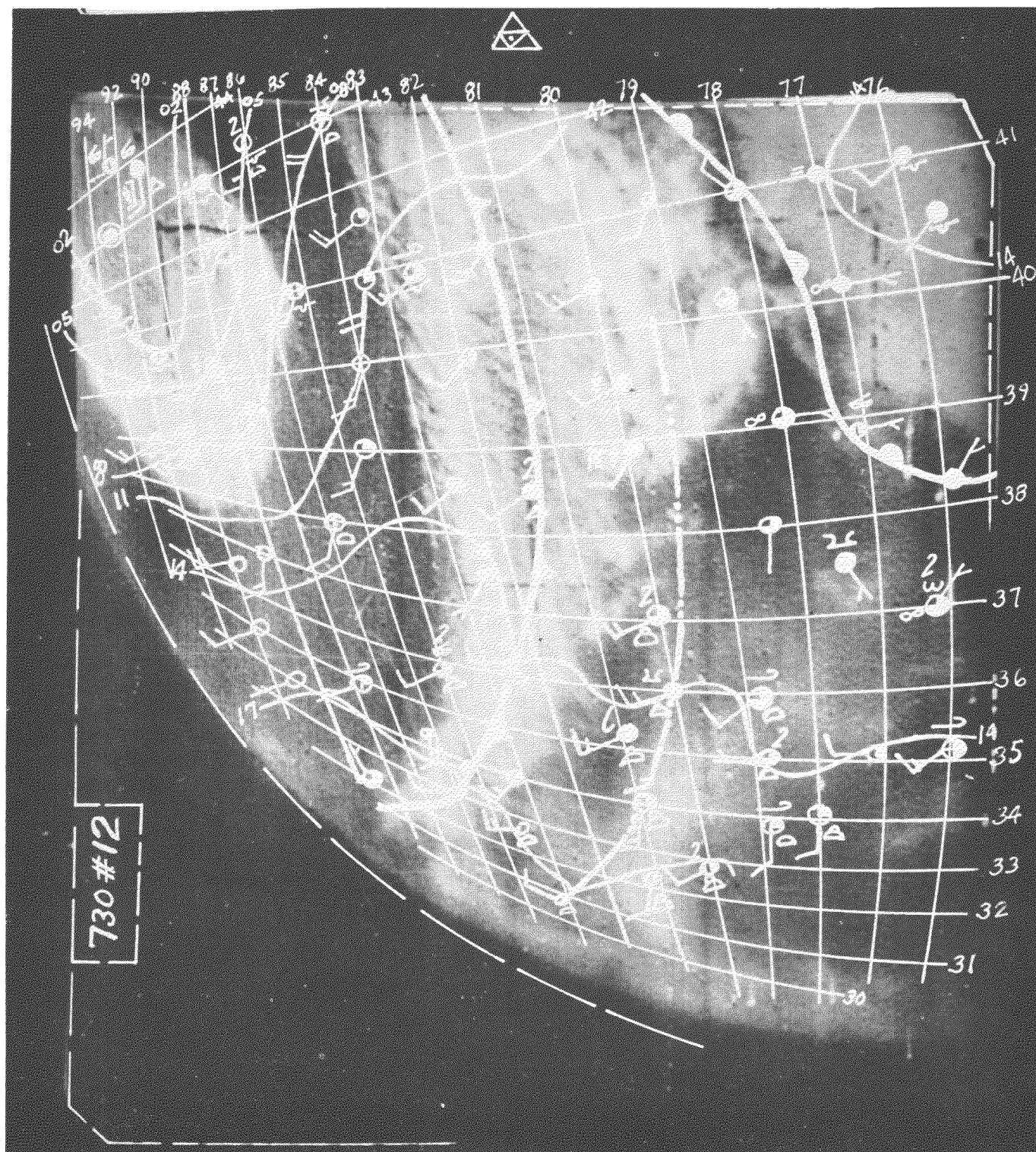


FIGURE 12.—TIROS picture for 1817 GMT, May 21, 1960 with data and latitude-longitude grids superimposed.

gone a 10-kt. increase and the rapid movement of the cold front produced a long bent-back occlusion over the Great Lakes. The cold front, especially south of 35° N., was undergoing frontolysis and had become shallow and diffuse.

A large change in the cloud distribution had taken place from that shown in figure 8a for the previous day. The cloud field associated with the cold front had become a very narrow band lying over the upslope side of the Appalachians and an expansive clear area with a long

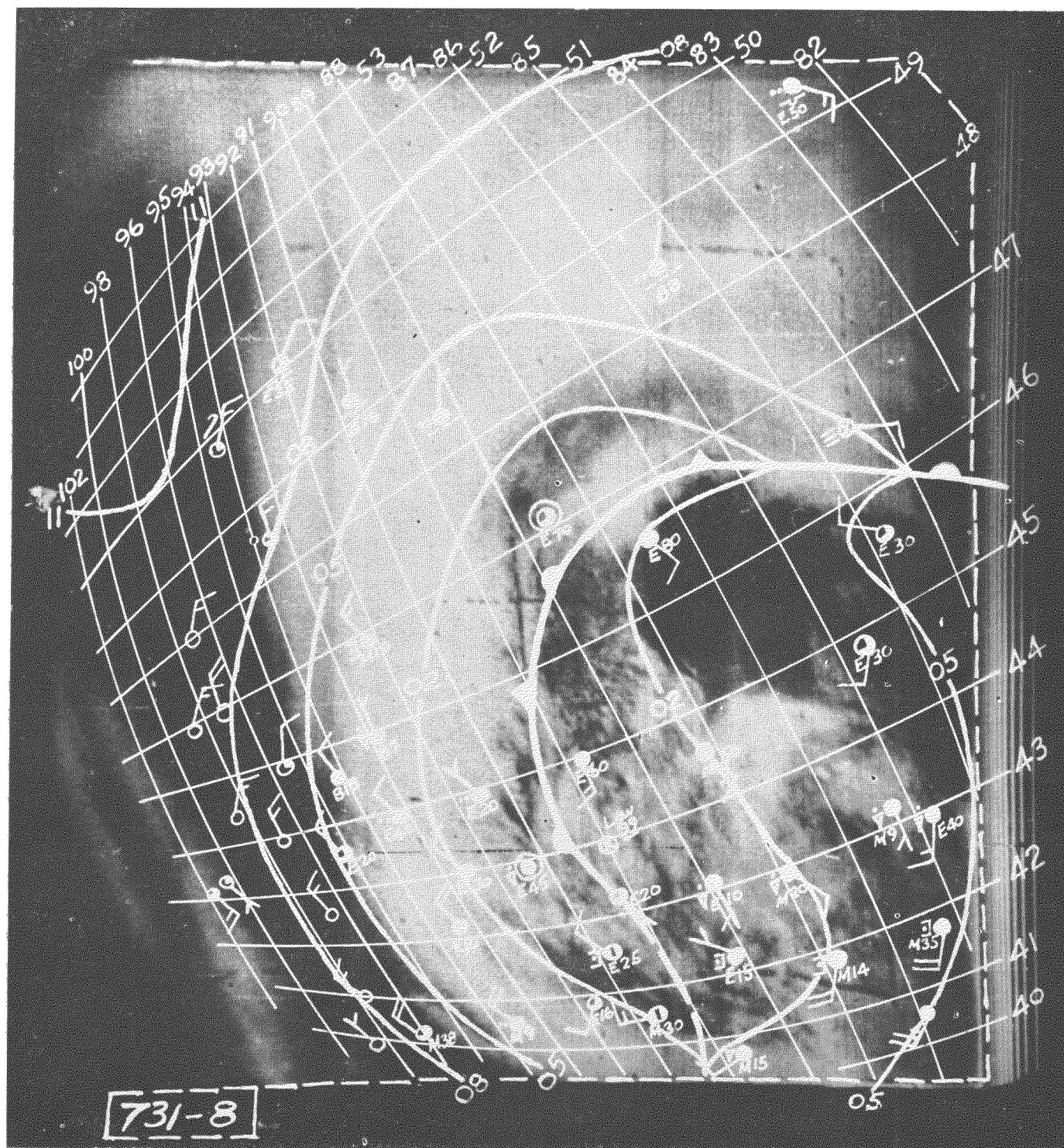


FIGURE 13.—TIROS picture for 2000 GMT, May 21, 1960 with data and latitude-longitude grids superimposed.

narrow curved clear tongue had developed behind the front. The broken section of clouds about 200 mi. east of the cold front partly reflected the weak instability line.

Cloud patterns on this day complied very nicely with the "ideal" distribution model.

LOW-LEVEL WIND MAXIMUM

Figure 15c shows the wind analysis at 1800 GMT, May 21, 1960 for the 5,000-ft. level. Figure 15a shows the nephanalysis with the axis superimposed. Notice that the axis coincided very closely with the sharp edge of the

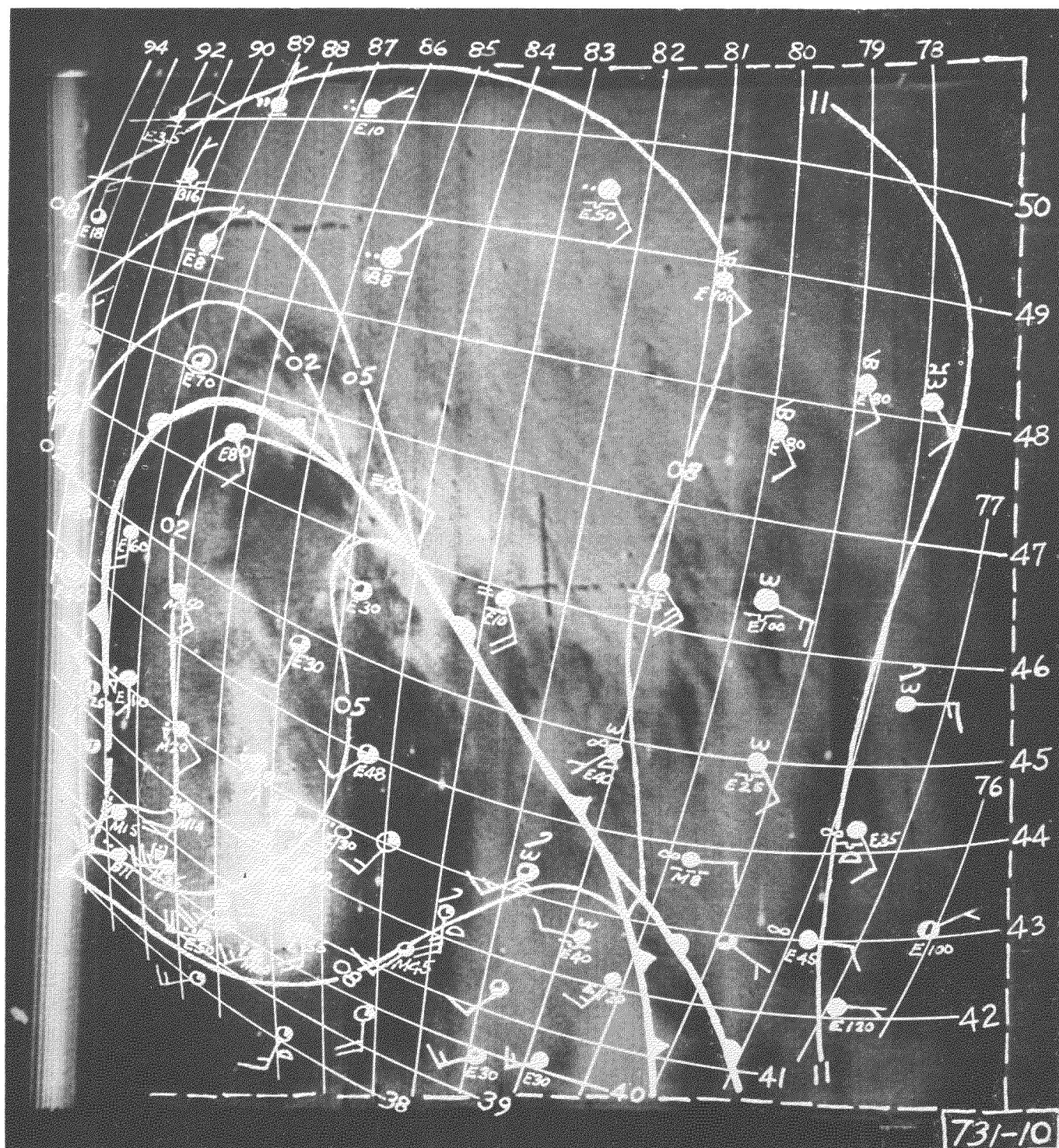


FIGURE 14.—TIROS picture for 2001 GMT, May 21, 1960 with data and latitude-longitude grids superimposed.

low cloud mass which was associated with the vortex to the north.

Examination of the vertical distribution of winds in this area showed that the jet stream at 35,000 ft. was positioned very nearly vertically above the maximum at 5,000 ft., while the intermediate axes about the 14,000-ft. level were located approximately 100 mi. toward the south.

The horizontal moisture advection computed for 1200

GMT, May 21 is shown in figure 16. Again, the strongest advection of dry air was occurring to the south of the maximum axis.

VERTICAL MOTIONS

The 600-mb. JNWP vertical motions showed broadscale downward motion over the Plains States west of the Mississippi Valley and a broad zone of upward motions en-

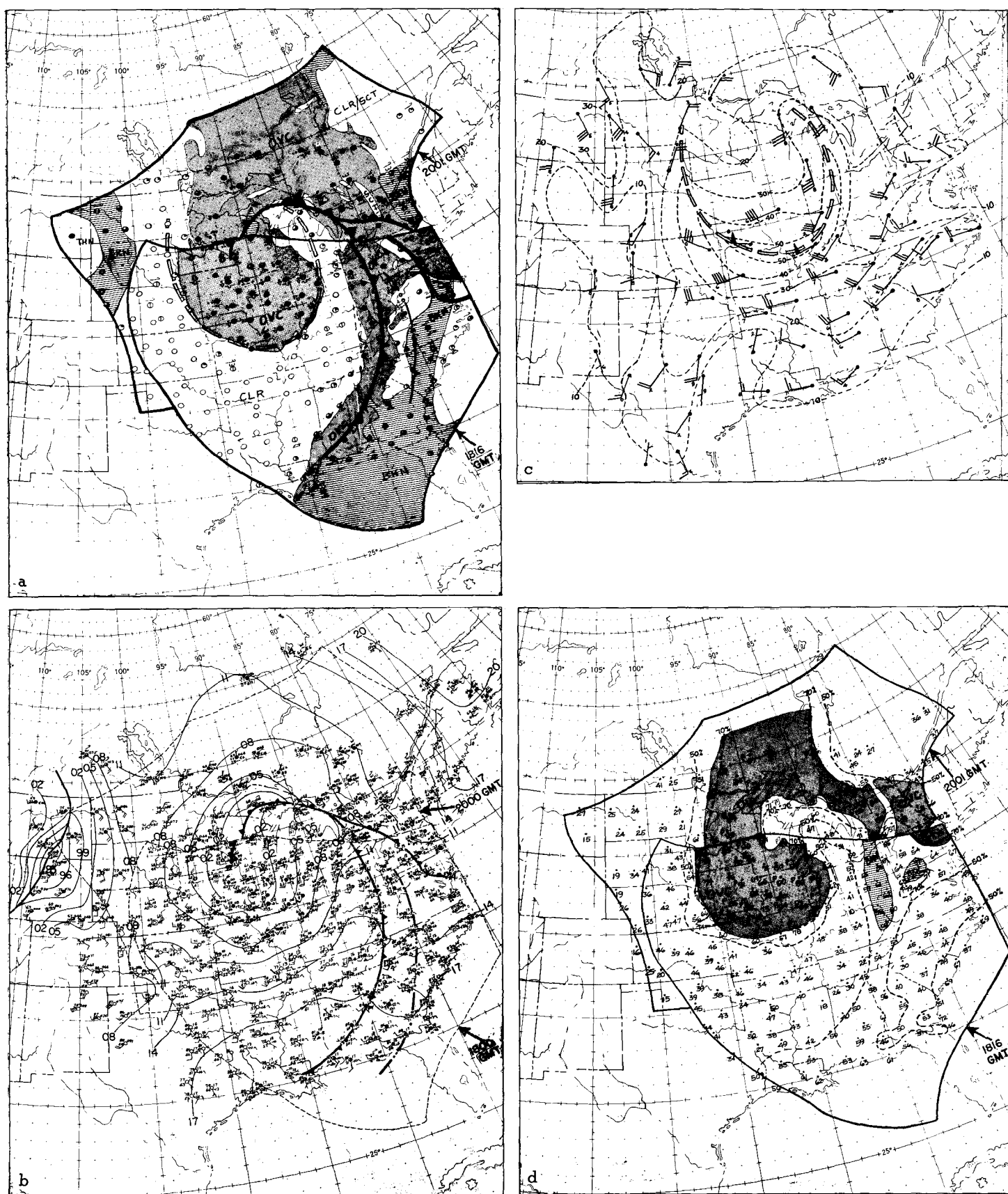


FIGURE 15.—(a) Schematic nephanalysis 1816–1817 and 2000–2001 GMT, May 21, 1960. Broken line shows axis of maximum wind at 5,000 ft. (from c). (b) Surface data and analyses 1800 and 2000 GMT, May 21, 1960. (c) Wind data, axis of maximum wind, and isotachs (kt.) at 5,000 ft., 1800 GMT, May 21, 1960. (d) Broken and overcast cloud ceilings below 5,000 ft. with surface relative humidity isopleths (percent), 1800 and 2000 GMT, May 21, 1960.

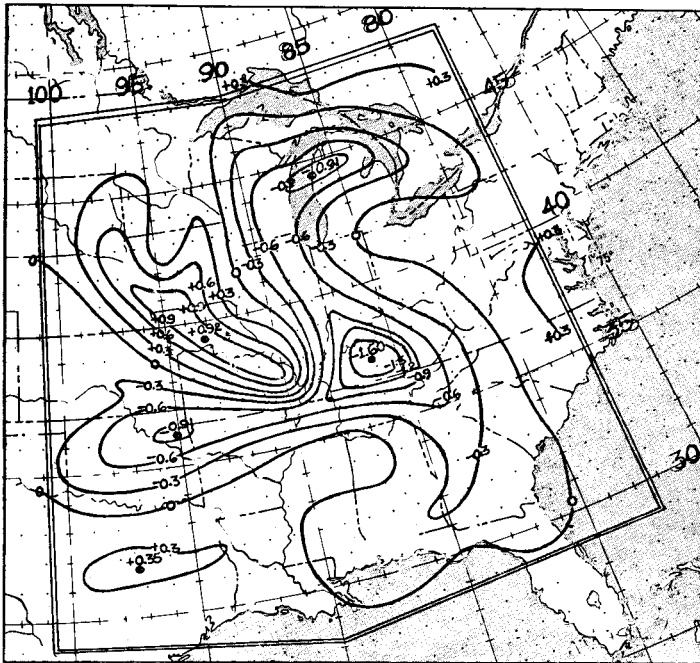


FIGURE 16.—850-mb. horizontal moisture advection ($\text{gm. kg.}^{-1} \text{ hr.}^{-1}$), 1200 GMT, May 21, 1960.

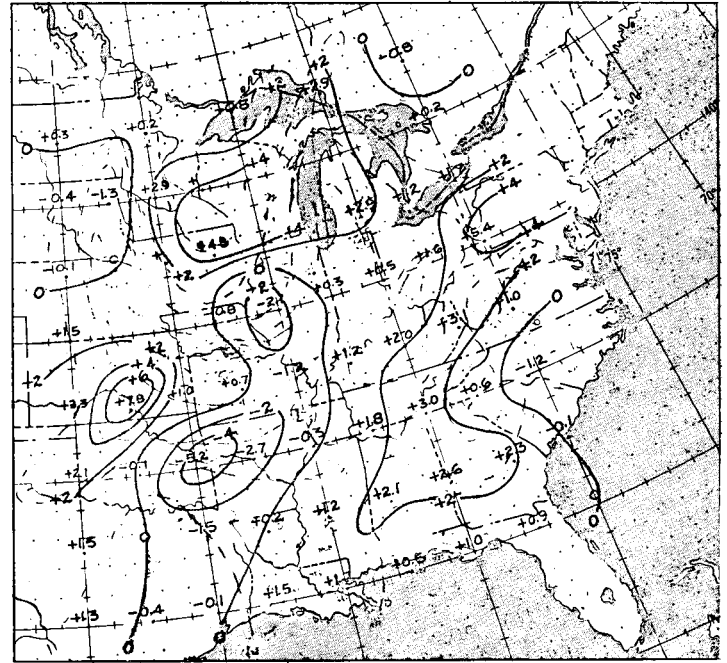


FIGURE 17.—850-mb. vertical motions (cm. sec.^{-1}) computed by the adiabatic method, 0000–1200 GMT, May 21, 1960.

gulfing the clear tongue and a portion of the large clear area to the rear of the cold front.

Careful nephanalyses of several sets of surface observations indicated that the strongest development of the clear tongue occurred between 1800 GMT, May 20 and 1200 GMT, May 21. For that reason, the mean vertical motions for the period 0000 to 1200 GMT, May 21 were computed by the adiabatic method [7] for the 850-mb. and 700-mb. levels. Figure 17 shows the vertical motions at 850 mb.

Areas near the Great Lakes were covered with clouds so that the computed vertical motions were based on moist adiabatic processes. At the grid points on figure 17 showing no values, the actual lapse rates were approximately equal to the moist adiabatic lapse rates and hence these computations failed because the stability approached zero. While it is not entirely satisfactory to use the adiabatic method at the 850-mb. level because of the influence of surface radiation, it is very likely that the downward motion yielded by this computation was correct in sign. This follows because the diabatic cooling of air from 7:00 p.m. to 7:00 a.m. would produce fictitious upward motions in the computation, so that downward motions were shown despite the masking effect of cooling. Upward motions, by the same token, are suspect and the vertical motion over the Appalachian Mountains may be spurious because the diabatic influence was maximized in that region.

Reliability of the computed motions was further attested to by the lapse rates about the 850-mb. level. Comparison of vertical motions at 850 mb. (fig. 17) and the lapse rates between 1 and 2 km. (fig. 10) indicated that the tongue of small lapse rates, about $3^{\circ}\text{--}4^{\circ} \text{ C. km.}^{-1}$, was

being produced by the similarly oriented tongue of downward motions.

Vertical motions at the 700-mb. level were similar to those computed at 850 mb., with some slope toward the north of the center at $35^{\circ} \text{ N.}, 95^{\circ} \text{ W.}$ The secondary center of downward motion at $40^{\circ} \text{ N.}, 90^{\circ} \text{ W.}$ was overlain with upward motion at 700 mb. In summary, from these computations it appears that subsidence in the low troposphere was concentrated on the anticyclonic shear side of the low-level jet and was producing dry air which was then advected rapidly into the long clear tongue that is shown in the pictures on May 21, 1960.

SURFACE RELATIVE HUMIDITY

Figure 15d shows the surface relative humidity patterns and the low cloud nephanalysis for May 21, 1960. The 70 percent humidity isopleth again closely delineated the areas of low cloud ceilings. Of the 235 stations for which surface humidity was available, not one station reported a low cloud ceiling when the humidity was below 50 percent; only 5 stations violated the prescribed 70 percent limitation by showing no low cloud ceilings with greater than 70 percent relative humidity.

Over these 5 stations, the lapse rates at 0000 GMT, May 22 again indicated that low-level stability was prevailing in the regions of the violations. The increase in area of greater lapse rates (greater than $6^{\circ} \text{ C. km.}^{-1}$) from that of the previous day further suggests that surface humidity is better correlated with low cloud cover when the air is nearly unstable and substantial mixing is occurring.

5. SUMMARY

Over the 3-day period, cloud distribution about the surface fronts conformed nicely with the "ideal" distribution models with the exception of the distribution about the cold front on May 19, 1960. On this day, clouds were found well to the rear of the cold front because the 500-mb. trough, with which the bulk of the clouds was associated, was located approximately 500 mi. to the rear of the surface frontal position. In such north-south cold frontal systems, the amount of cloudiness behind the surface front may be an indicator of the slope of the upper-air system.

The long clear tongue shown in figures 12 and 14 developed in the region of a low-level wind maximum. This striking feature, which appears to be a frequent mark of this type of synoptic situation, was caused by the development of a strong band of subsidence on the anticyclonic shear side of the low-level wind maximum. This strong subsidence at both the 850- and 700-mb. levels, on the anticyclonic shear side of the maximum wind speed intensified the horizontal advection of dry air and hence the clearing far downstream from the isotach maximum.

The 600-mb. JNWP vertical motions computed by the present model reflected some large-scale vertical motion fields. Clouds were sometimes photographed in areas of computed downward motion and often no clouds were found in areas of upward motion. The vertical motions computed by the adiabatic method for the period 0000–1200 GMT, May 21 agreed quite well with the cloudiness observed at 0600 GMT, May 21.

There was a high correlation between surface humidity and low cloud cover. Over the 3-day period, of the 660 stations examined, only 54 violated the 50 percent and 70 percent limitations and each of these 54 violations fell within 120 miles of the prescribed humidity isopleth. In general, the following relationships were seen: (a) low cloud cover was overcast where surface humidity was 80 percent or greater; (b) low cloud ceilings (broken to overcast) were observed where the surface relative humidity was 70 percent or greater; (c) relative humidities of 50 percent to 70 percent were the middle ground where low cloud coverage was both smaller and greater than 5/10; (d) low cloud ceilings were not reported where surface humidity was below 50 percent.

The strong relationship between surface humidity and low cloud cover appears to be characteristic of summer afternoon regimes where strong surface heating produces instability in the low levels and thus allows substantial mixing of the subcloud layer. It was seen that the poorest agreement of the surface humidity and low cloud cover existed over areas of very small lapse rates (stable conditions). On the other hand, when lapse rates were larger (more unstable conditions) there was considerable vertical mixing of a moist layer such that surface humidities were closely related to low cloud cover.

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